Gap Waveguide Flat Luneburg lens antenna at millimeter waves

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Abstract

In this paper, a flat lens antenna using Gap Waveguide (GW) technology working in the millimeter waves band is designed. The metamaterial lens is fed using a Groove Gap Waveguide (GGW) horn antenna in order to achieve a planar wavefront at broadside. Both devices, metalens and GGW antenna achieve excellent radiation results when combined together. Due to the fully metallic composition, the structure presents more robustness, low loss, and adaptability to a flat surface, apt for millimeter wave application.

1. Introduction

With the rapid development of modern wireless communication technology, the fifth-generation (5G) mobile standard and Internet of Things (IoT), the 60 GHz frequency band has received special attention due to its potential functional benefits. The demand for faster speed, the greater volume of information required and multibeam antennas with high gain, are new challenges faced by the engineering community that still lack from a satisfactory solution.

A fundamental obstacle that must be circumvented to achieve a full development of high frequency technology is the low loss surface wave guiding. Traditional feeding systems like waveguides and microstrip lines suffer from increasing loss as the frequency grows. In the last decade, Gap Waveguide (GW) technology has gained a lot of interest since it consists a reliable and competitive alternative for high-frequency communications [1] with three main variants: groove-gap waveguide (GGW) [2], ridge-gap waveguide (RGW) [3] and microstrip-gap waveguide (MGW) [4]. GW shows considerable improvements compared to standard metallic waveguides, such as low losses, non-compulsory electric contact and effortless adaptability to flat surfaces [5]. It also has a lower manufacturing cost with respect to traditional hollow waveguides, since the tolerances are coarser alleviating the fabrication constraints.

Beyond that, it is evident that designing a high gain and broadband antenna using this technology opens new avenues for high frequency communications. There is an increasing interest in metasurface (MTS) antennas due to their ability to provide high gains, while at the same time maintaining a light weight and a low profile, making them excellent candidates for lens antenna applications such as the Luneburg Graded Index (GRIN) lens [6]. In order to improve the antenna characteristics, an appealing idea is to use classic antennas in GW technology and combine them with metalenses. Therefore, the main objective of this investigation is to combine these technologies to have antennas with good radiation characteristics and compatible with the implementation of 5G mobile communications.

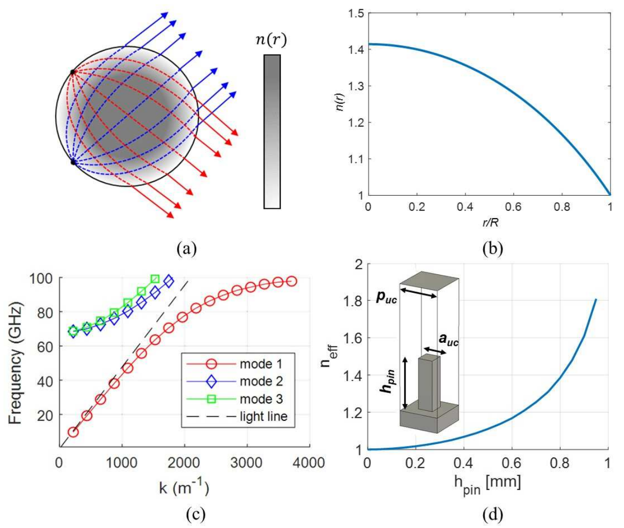

Figure 1. (a) Top view of the standard Luneburg lens with a ray tracing sketch (red and blue arrows) describing the operation. (b) Equivalent refractive index of a 2D Luneburg lens as a function of the normalized radius *r/R*, where R is the outer lens radius. (c) Dispersion diagram of a metallic pin [shown in the inset of panel (d)] with the following dimensions: $p_{uc} = 0.8$ mm, $a_{uc} = 0.3$ mm and $h_{ground} = 0.75$ mm. (d) Equivalent refractive index as a function of the unit-cell's pin height hpin at $f_0 = 60$ GHz.

2. Design of the Lens

Typically, metasurfaces consist of subwavelength patches or slots arranged in a regular lattice [5]. By loading a Parallel Plate Waveguide (PPW) with a fakir's bed of nails consisting of metallic posts with different heights, one is able to provide TM surface wave manipulation in order to produce an artificial dielectric [7]-[8]. In this work, a metal-only metasurface antenna is implemented in order to overcome the losses associated with dielectric lens antennas in the microwave band, as well as to provide structural integrity to the antenna in harsh environmental conditions [9]-[10].

The Luneburg lens (LL) was proposed in [6] and features a spatially varying refractive index distribution which is characterized by rotational symmetry, see Fig. 1(a). When fed by a source placed at its focal circumference, a LL collimates the rays, producing a plane wave in the opposite side of the lens. The focusing properties of a LL are only defined by the refractive index distribution *n(r)*, which means that the lens is capable of generating directive beams independently of the frequency. Starting from this concept, a planar LL is considered in the V-band as it offers a full azimuthal scanning in the form of fan beams. The refractive index of a LL follows the next equation:

$$n(r) = \sqrt{2 - (r/R)^2} \qquad (1)$$

where r is the radial component and R is the outer lens radius.

The dispersion diagram of the unit-cell [presented in Fig. 1(c)] has been obtained by a full wave periodic solver (more specific, the frequency solver from CST Microwave Studio®). This diagram displays unimodal propagation with a linear, non-dispersive behavior in a large bandwidth within the considered frequency range, which makes this unit-cell a suitable candidate for the realization of the lens. The design parameters are the periodicity of the unit-cell (p_{uc}), the width of the metallic post (a_{uc}) and its height (h_{pin}). By varying h_{pin}, it is possible to derive an effective refractive index at a single frequency, as depicted in Fig. 1(d).

Matching the posts height to the profile of the LL, we can construct the final geometry of the metasurface lens by mapping the corresponding height of each unit cell with respect to the bottom metallic plane. The lens has a radius equal to $5\lambda_0$ and a PPW height of d = 2.1 mm above the maximum metallic post height ($h_{uc,max}$ = 1.3 mm), where λ_0 is the free space wavelength at the design frequency f_0 = 60 GHz. A conventional H-plane sectoral horn antenna is used to feed the lens system with satisfactory results, as shown in Figs. 2 (a) and (b).

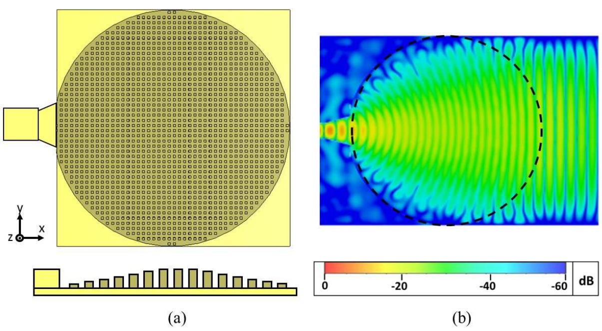

Figure 2. (a) Top view (top) and cross section (bottom) of the Luneburg lens fed by horn antenna. (b) Electric field magnitude |Re{Ez}| at 58 GHz for the planar PPW Luneburg lens of radius $R = 5\lambda_0$ fed by an H-plane sectoral horn.

3. Simulation Results

Up to this point, we have modulated a surface using a bed of nails to achieve the LL behavior and have excited it with a classical metallic horn. The next step is to feed the LL by a horn antenna made in GGW technology. We performed a design and numerical analysis using the commercial simulator CST Microwave Studio® [11].

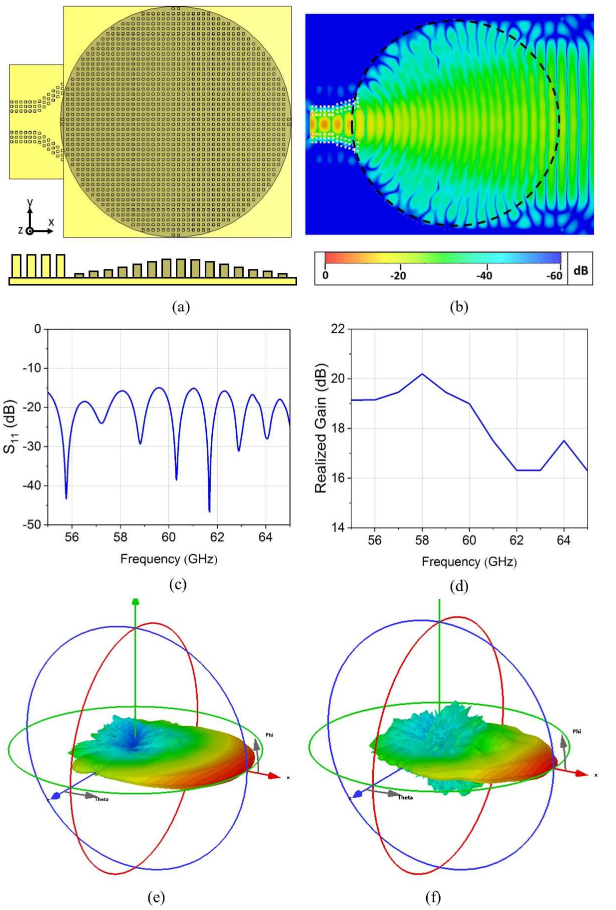

Figure 3. (a) Top view (top) and cross section (bottom) of the Luneburg lens fed by a GGW horn antenna. (b) Normalized electric field magnitude |Re{Ez}| at 58 GHz in decibel scale. Simulated results of the structure. (c) Magnitude of the reflection coefficient in dB. (d) Peak realized gain vs frequency. Radiation patterns of (c) Luneburg lens fed by horn antenna and (d) Luneburg lens fed by GGW horn antenna.

Applying the theory in [1], the main objective is to achieve a similar phase center than the classical horn antenna to feed the LL shown in Fig. 3(a). The GGW horn antenna was placed on the metasurface focal circumference, in order to obtain radiation characteristics similar to the previous case. In this case, a single pin of height h = 1.5

mm and periodicity p = 1 mm generates a bandgap around 40-80 GHz so the wave can be effectively guided by a periodic structure made of these pins at the operation frequency. Finally, Fig. 3(b) shows the normalized vertical component of the electric field from a top view. Analyzing it in detail, it is clear that we achieve a planar wave front in the direction of propagation, in good agreement with the previous results using a conventional H-plane sectoral horn, Fig. 2(b). It is clearly seen that the lens shapes the wave front from the GGW horn antenna into a plane wave. Therefore, the GGW horn antenna provides similar radiation characteristics and when combined with the LL improves the results in a more compact design.

Fig. 3(c) shows the simulation results of the considered structure. First, we note that the antenna is matched in the entire operation band (from 55 to 65 GHz), with the criterion of having a reflection coefficient magnitude below −10 dB (see Fig. 3(c)). The prototype has a high gain with a maximum around 20 dB at 58 GHz, Fig. 3(d). Furthermore, the gain bandwidth is around 10.3 % close to 6 GHz, assuming a loss of −3 dB from peak gain. Finally, a comparison between the radiation patterns at 58 GHz is shown in Figs. 3(e) and (f).

4. Conclusions

To sum up, this article presents the design of a LL excited by a GW horn antenna. The metamaterial LL has been synthesized using metallic pins to modulate a specific permittivity in order to achieve a plane wave in the direction of propagation. A GGW horn antenna has been also designed, and combined with the metasurface achieving excellent radiation characteristics. Furthermore, owing to its fully metallic structure and design, this system has more robustness, low loss and adaptability to planar surfaces.

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